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(54) Method and apparatus for electric/acoustic telemetry in a well.

(57) A drill collar section (22) of a drill string (16) (i.e. at the downhole end of the drill string) includes an electric transmitter/receiver assembly (26) which communicates with an electric/acoustic repeater assembly (28) which communicates with an acoustic transmitter/ receiver assembly (29) uphole of the drill string by the transmission and receipt of electric and acoustic signals through the drill string. With drill strings that include downhole motors (30) the electric transmitter/receiver assembly may be positioned above or below the motor. Uphole telemetry comprises an electric current induced in the drill string by the downhole electric transmitter (26). The electric current contains encoded information of downhole conditions and travels up the drill string where it is detected at the electric receiver of the electric/acoustic repeater (28). The received signal is processed to drive the acoustic transmitter of the electric/acoustic repeater. An acoustic signal containing the encoded information is induced into the drill string by this acoustic transmitter and permeates up the drill string to the uphole acoustic receiver (29). This received signal is processed and utilized to evaluate and/or optimize the drilling process or to evaluate the earth formations being drilled. Downhole telemetry comprises an acoustic signal induced in drill string (16) by the uphole acoustic transmitter (29). The acoustic signal contains encoded information of uphole commands and travels down the drill string where it is detected at the acoustic receiver of the electric/acoustic repeater (28). The received signal is processed to drive the electric transmitter of the electric/acoustic repeater. An electric signal containing the encoded information is induced in the drill string by this electric transmitter and travels down the drill string to the downhole electric receiver (26). This received signal is processed and utilized to command a downhole processor (i.e., computer).

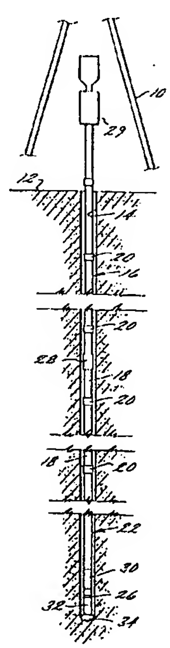

FIG. 4

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The present invention relates generally to a downhole telemetry system for facilitating the transfer of borehole and drilling data to the surface for inspection and analysis. More particularly, the invention relates to a measurement-while-drilling ("MWD") system that senses and transmits data measurements from a downhole location to an uphole location.

Deep wells of the type commonly used for petroleum or geothermal exploration are typically less than 30 cm (12 inches) in diameter and on the order of 2 km (1.5 miles) long. These wells are drilled using drill strings assembled from relatively light sections (either 30 or 45 feet (9.1 or 13.7m) long) of drill pipe that are connected end-to-end by tool joints, additional sections being added to the uphole end as the hole deepens. The downhole end of the drill string typically includes a drill collar, a dead weight assembled from sections of relatively heavy lengths of uniform diameter collar pipe having an overall length on the order of 300 meters (1000 feet). A drill bit is attached to the downhole end of the drill collar, the weight of the collar causing the bit to bite into the earth as the drill string is rotated from the surface. Sometimes, downhole mud motors or turbines are used to turn the bit. Drilling mud or air is pumped from the surface to the drill bit through an axial hole in the drill string. This fluid removes the cuttings from the hole, provides hydrostatic head which controls the formation gases, and sometimes provides cooling for the bit.

Communication between downhole sensors of parameters such as pressure or temperature and the surface has long been desirable. There are a number of systems in the prior art which seek to transmit information regarding parameters downhole up to the surface. There prior systems may be descriptively characterized as: (1) mud pressure pulse; (2) hardwire connection; (3) acoustic wave; and (4) electromagnetic waves.

In a mud pressure pulse system, the drilling mud pressure in the drill string is modulated by means of a valve and control mechanism mounted in a special pulsar collar above the drill bit and motor (if one is used). The pressure pulse travels up the mud column at or near the velocity of sound in the mud, which is approximately 4000-5000 feet per second (1200-1500 m/s). The rate of transmission of data, however, is relatively slow due to pulse spreading, modulation rate limitations, and other disruptive forces, such as the ambient noise in the drill string. A typical pulse rate is on the order of a pulse per second. A representative example of mud pulse telemetry systems may be found in U.S. Patent Nos. 3,949,354, 3,964,556, 3,958,217, 4,216,536, 4,401,134, 4,515,225, 4,787,093 and 4,908,804.

Hard-wire connectors have also been proposed to provide a hard wire connection from the bit to the surface. There are a number of obvious advantages to using wire or cable systems, such as the ability to transmit at a high data rate; the ability to send power downhole; and the capability of two-way communication. Examples of hard wire systems may be found in U.S. Patent Nos. 3,879,097, 3,918,537 and 4,215,426.

The transmission of acoustic or seismic signals through a drill pipe or the earth (as opposed to the drilling mud) offers another possibility for communication. In such a system, an acoustic or seismic generator is located downhole near or in the drill collar. Typically a large amount of power is required downhole to generate a signal with sufficient intensity to be detected at the surface. One way to provide sufficient power downhole (other than running a hard wire connection downhole) is to provide a large power supply downhole. Further, one reason for the large power requirement is that when the acoustic transmitter is located downhole near the bit a large acoustic signal is required to overcome the acoustic noise generated by the bit during drilling so that the transmitted acoustic signal can be distinguished from the downhole acoustic noise. An example of an acoustic telemetering system is Cameron Iron Works' CAMSMART downhole measurement system, as published in the Houston Chronicle on May 7, 1990, page 3B. Other examples of acoustic telemetry systems are found in U.S. Patent Nos. 5,050,132, 5,056,067, 5,124,953, 5,128,901, 5,128,902 and 5,148,408.

The last major prior art technique involves the transmission of electromagnetic ("EM") waves through a drill pipe and the earth. In this type of system, downhole data is input to an antenna positioned downhole in a drill collar. Typically, a large pickup assembly or loop antenna is located around the drilling rig, at the surface, to receive the EM signal transmitted by the downhole antenna.

The major problem with the prior art EM systems is that a large amount of power is necessary to transmit a signal that can be detected at the surface. Propagation of EM waves is characterized by an increase in attenuation with an increase in distance, data rate and earth conductivity. The distance between the downhole antenna and the surface antenna may be in the range of 5,000 to 10,000 feet (1500 to 3000m). As a result, a large amount of attenuation occurs in the EM signal, thereby necessitating a more powerful EM wave. The conductivity of the earth and the drilling mud also may vary significantly along the length of the drill string, causing distortion and/or attenuation of the EM signal. In addition, the large amount of noise in the drilling string causes interference with the EM wave.

The primary way to supply the requisite amount of power necessary to transmit the EM wave to the surface is to provide a large power supply downhole or to run a hard wire conductor downhole. Representative examples of EM systems can be found in U.S.

Patent Nos. 2,354,887, 3,967,201, 4,215,426, 4,302,757, 4,348,672, 4,387,372, 4,684,946, 4,691,203, 4,710,708, 4,725,837, 4,739,325, 4,766,442, 4,800,385 and 4,839,644.

There have been attempts made in the prior art to reduce the effects of attenuation which occur during the transmission of an EM signal from down near the downhole drilling assembly to the surface. U.S. Patent No. 4,087,781, issued to Grossi, et al., for example, discloses the use of repeater stations to relay low frequency signals to and from sensors near the drilling assembly. Similarly, U.S. Patent No. 3,793,632 uses repeater stations to increase data rate and, in addition, suggests using two different modes of communication to prevent interference. U.S. Patent Nos. 2,411,696 and 3,079,549 also suggest using repeater stations to convey information from downhole to the surface. None of these systems has been successful, based primarily on the varying conditions encountered downhole, where conductivity may range over several orders of magnitude.

Another method of transmitting MWD information to the surface using electromagnetic transmission is described in an article entitled Air-Drilling Electromagnetic, MWD System Development, IADC/SPE, 1990 by W.H. Harrison et al, which is incorporated herein by reference. One problem with electromagnetic transmission is the high attenuation of EM signals in highly conductive formations. Referring to FIGURE 1 herein the attenuation against source receiver distance is plotted for a 0.2 ohm-meter formation for frequencies of 1, 5, 10, 15 and 20 Hertz. These calculations are made using the method described in an article entitled Theory of Transmission of Electromagnetic Waves Along a Drill Rod in Conducting Rock, 1979 by James R. Wait and David A. Hill, which is incorporated herein by reference.

In practice an acceptable total attenuation is about 90 dB. However, in the Harrison et al article it is erroneously claimed that 120 dB of attenuation is practical. The slope of the curves (FIGURE 1) at 5000' (1500m) distance is noted on the plot. This attenuation slope for 20 Hz is 53 dB per 1000 feet (300m) which is clearly too high for practical transmission for any large distance. At 10 Hz the attenuation of 37 dB per 1000 feet (300m) is still very high, but it would at least allow about 2000 feet (600m) of effective transmission. The reduction of the frequency of operation to 1 Hz (11.86 dB per 1000 feet (300m)) or perhaps 2 Hz would be required for long distance communication at resistivities as low as 0.2 ohm-meters. At such a low frequency the electric transmission method has no real advantage over current mud pulse technology.

The above-discussed and other problems and deficiencies of the prior art are overcome or alleviated by the method and apparatus for electric/acoustic telemetry of the present invention, which relates to a MWD system that senses and electrically transmits data measurements from a downhole location to an electric/acoustic repeater which acoustically transmits the data measurements to an acoustic receiver at an uphole location. In the present invention, one of the drill collar sections of a drill string (i.e., at the downhole end of the drill string) includes an electric transmitter/receiver assembly which communicates with an electric/acoustic repeater assembly which communicates with an acoustic transmitter/receiver assembly uphole of the drill string by the transmission and receipt of electric and acoustic signals through the drill string. With drill strings that include downhole motors the electric transmitter/receiver assembly may be positioned above or below the motor.

In accordance with one aspect of the present invention, there is provided an apparatus for transmitting information through a drill string having an upper end and a lower end with a drill bit disposed at the lower end, comprising: means for transmitting an electromagnetic data signal from a first location near the lower end of the drill string; means for receiving said electromagnetic data signal at a second location between the lower and upper ends of the drill string; means for transmitting an acoustic data signal from said second location in response to said electromagnetic data signal received; and means for receiving said acoustic data signal at third location at or near the upper end of the drill string.

In the present invention, uphole telemetry comprises an electric current induced in the drill string by the downhole electric transmitter. The electric current contains encoded information of downhole conditions and travels up the drill string where it is detected at the electric receiver of the electric/acoustic repeater. The received signal is processed to drive the acoustic transmitter of the electric/acoustic repeater. An acoustic signal containing the encoded information is induced into the drill string by this acoustic transmitter and permeates up the drill string to the uphole acoustic receiver. This received signal is processed and utilized to evaluate and/or optimize the drilling process.

In the present invention, downhole telemetry comprises an acoustic signal induced in drill string by the uphole acoustic transmitter. The acoustic signal contains encoded information of uphole commands and travels down the drill string where it is detected at the acoustic receiver of the electric/acoustic repeater. The received signal is processed to drive the electric transmitter of the electric/acoustic repeater. An electric signal containing the encoded information is induced in the drill string by this electric transmitter and travels down the drill string to the downhole electric receiver. This received signal is processed and utilized to command a downhole processor (i.e., computer).

The present invention resolves the prior art prob-

lems encountered with electromagnetic and acoustic telemetry by utilizing: (1) electric telemetry (electromagnetic telemetry) downhole, thereby avoiding the problem of detection at the surface; and (2) acoustic telemetry uphole, thereby avoiding the problem of acoustic noise near the bit (i.e., downhole).

The above-discussed and other features of and advantages of the present invention will be appreciated, and understood by those skilled in the art from the following detailed description and drawings.

A number of preferred embodiments of the present invention will now be described by way of example only and with reference to the accompany drawings wherein like elements are numbered alike in the several FIGURES, and in which:

FIGURE 1 is a plot of amplitude versus source receiver distance for a 0.2 ohm-meter formation in accordance with the Wait et al model;

FIGURE 2A is a perspective view of a prior art rotary drilling system;

FIGURE 2B is a partially sectional front elevation of a prior art steerable drilling system;

FIGURE 3 is a cross-sectional elevation view depicting a downhole drilling apparatus and drill string employing an electric/acoustic telemetry system in accordance with the present invention;

FIGURE 4 is a cross-sectional elevation view depicting a downhole drilling apparatus and drill string employing an electric/acoustic telemetry system in accordance with an alternate embodiment of the present invention;

FIGURE 5 is a cross-sectional elevation view depicting a downhole drilling apparatus and drill string employing an electric/acoustic telemetry system in accordance with still another alternate embodiment of the present invention;

FIGURE 6 is a cross-sectional elevation view of the downhole electromagnetic antenna;

FIGURE 7 is a plot of amplitude versus source receiver distance for a 1.0 ohm-meter formation in accordance with the Wait et al model;

FIGURE 8 is a plot of amplitude versus source receiver distance for a 10.0 ohm-meter formation in accordance with the Wait et al model;

FIGURE 9 is a plot of amplitude versus source receiver distance for a 1.0 ohm-meter formation in accordance with an electric dipole model; and

FIGURE 10 is a plot of amplitude versus source receiver angle for a 1.0 ohm-meter formation in accordance with the electric dipole model.

During the course of the following description, the terms "uphole", "upper", "above" and the like are used synonymously to reflect position in a well path, where the surface of the well is the upper or topmost point. Similarly, the terms "bottomhole", "downhole", "lower", "below" and the like are also used to refer to position in a well path where the bottom of the well is the furthest point drilled along the well path from the surface, and the term "subsurface" indicates a downhole location remote from the surface of the well. As one skilled in the art will realize, a well may vary significantly from the vertical, and, in fact, may at times be horizontal. Thus, the foregoing terms should not be regarded as relating to depth or verticality, but instead should be construed as relating to the position in the path of the well between the surface and the bottom of the well.

Two prior art drilling systems are shown in FIGURES 2A and 2B. FIGURE 2A illustrates a prior art drilling system that operates solely in a rotary mode, while FIGURE 2B depicts a prior art steerable system that permits both straight and directional drilling. The rotary drilling system shown in FIGURE 2A includes a drill bit with a telemetry device for relaying data to the surface. Above the telemetry device is a sensor sub which includes a variety of sensors for measuring parameters in the vicinity of the drill collar, such as resistivity, gamma, weight-on-bit, and torque-on-bit. The sensors transmit data to the telemetry device, which in turn, transmits a signal to the surface.

A non-magnetic drill collar typically is located above the sensor modules. Typically, the drill collar includes a directional sensor probe. The drill collar connects to the drill string, which extends to the surface.

Drilling occurs in a rotary mode by rotation of the drill string at the surface, causing the bit to rotate downhole. Drilling fluid (e.g., drilling mud) is forced through the interior of the drill string to lubricate the bit and to remove cuttings at the bottom of the well. The drilling mud then circulates back to the surface by flowing on the outside of the drill string.

The prior art steerable system shown in FIGURE 2B has the added ability to drill in either a straight mode or in a directional or "sliding" mode, as shown in U.S. Patent No. 4,667,751, which is incorporated herein by reference. The steerable system includes a motor which functions to operate the bit. In a prior art motor, such as that disclosed in U.S. Patent No. 4,667,751, the motor includes a motor housing, a bent housing, and a bearing housing. The motor housing preferably includes a stator constructed of an elastomer bonded to the interior surface of the housing and a rotor mating with the stator. The stator has a plurality of spiral cavities, n, defining a plurality of spiral grooves throughout the length of the motor housing. The rotor has a helicoid configuration, with n-1 spirals helically wound about its axis (e.g., see U.S. Patent Nos. 1,892,217, 3,982,858 and 4,051,910).

During drilling operations, drilling fluid is forced through the motor housing into the stator. As the fluid passes through the stator, the rotor is forced to rotate and to move from side to side within the stator, thus creating an eccentric rotation at the lower end of the rotor.

The bent housing includes an output shaft or con-

necting rod, which connects to the rotor by a universal joint or knuckle joint. According to conventional techniques, the bent housing facilitates directional drilling (e.g. see U.S. Patent Nos. 4,299,296 and 4,667,751). To operate in a directional mode, the bit is positioned to point in a specific direction by orienting the bend in the bent housing in a specific direction. The motor then is activated by forcing drilling mud therethrough, causing operation of the drill bit. As long as the drill string remains stationary (it does not rotate), the drill bit will drill in the desired direction according to the arc of curvature established by the degree of bend in the bent housing, the orientation of the bend and other factors such as weight-on-bit. In some instances, the degree of bend in the bent housing may be adjustable to permit varying degrees of curvature (e.g., see U.S. Patent Nos. 4,067,404 and 4,077,657). Typically, a concentric stabilizer also is provided to aid in guiding the drill bit (e.g. see U.S. Patent No. 4,667,751).

To operate in a straight mode, the drill string is rotated at the same time the motor is activated, thereby causing a wellbore to be drilled with an enlarged diameter (e.g. see U.S. Patent No. 4,667,751). The diameter of the wellbore is directly dependent on the degree of bend in the bent housing and the location of the bend. The smaller the degree of bend and the closer the placement of the bend is to the drill bit, the smaller will be the diameter of the drilled wellbore.

Referring to FIGURE 3, a schematic of a drill string utilizing an electric/acoustic telemetry system of the present invention is shown. A drilling rig 10 is positioned on the surface 12 above a borehole 14 which is traversed by a drill string 16. Drill string 16 is assembled from sections of drill pipe 18 that are connected end-to-end by tool joints 20. It will be appreciated that additional sections of drill pipe 18 are added to the uphole end of drill string 16 as the hole deepens. The downhole end of the drill string includes a drill collar 22 comprised of drill collar pipe having a diameter which is relatively larger than the diameter of drill pipe sections 18. Drill collar section 22 includes a bottom hole assembly 23 which terminates at a drill bit 24 and which may include several drill collar sections housing downhole sensors for sensing parameters such as pressure, position, resistivity or temperature. In accordance with the present invention, one of the drill collar sections 25 includes an electric transmitter/receiver assembly 26 which communicates with an electric/acoustic repeater assembly 28 which communicates with an acoustic transmitter/receiver assembly 29 uphole of drill string 16 by the transmission (and receipt) of electric and acoustic signals through the drill string.

Referring to FIGURE 4, in accordance with an alternate embodiment the downhole end of the drill string includes drill collar 22 and a motor 30 with an extended sub 32 connected to a drill bit 34. Electric transmitter/receiver assembly 26 is disposed at sub 32 along with at least one downhole sensor. In this embodiment electric transmitter/receiver assembly 26 and at least one downhole sensor are located downhole of motor 30.

Referring to FIGURE 5, in accordance with still another alternate embodiment the downhole end of the drill string includes drill collar 22 with one of the drill collar sections 35 including electric transmitter/receiver assembly 26 and motor 30 connected to drill bit 34. Downhole sensors are disposed at a drill collar section 36. In this embodiment electric transmitter/receiver assembly 26 and the downhole sensors are located uphole of motor 30.

Motor 30, for example, comprises a Dyna-Drill positive displacement motor with a bent housing, made by Smith International, Inc. as described hereinbefore and as shown in U.S. Patent No. 4,667,751. Other motors, including mud turbines, mud motors, Moineau motors, creepy crawlers and other devices that generate motion at one end relative to the other, may be used without departing from the principles of the present invention.

Referring again to FIGURE 4, motor 30 in accordance with the preferred embodiment, connects to extended sub 32 which houses at least one sensor module and communicates via electric transmitter/receiver assembly 26. One particular advantage of this embodiment is that the extended sub 32 may be removed and used interchangeably in a variety of downhole assemblies.

Referring to FIGURE 6 electric transmitter/receiver assembly 26 comprises a sensor antenna 38 (e.g. a toriod) mounted in an annular channel 40 of the drill collar section 25 (FIGURE 3), 32 (FIGURE 4), 35 (FIGURE 5). As is well known in the art, the toriod includes a core 42 and an electrical conductor 44 wrapped around the core. Core 42 is preferably comprised of a highly permeable material, such as an iron/nickel alloy. In the preferred construction, the alloy is formed into laminated sheets coated with insulation such as magnesium oxide, wound about a mandrel to form the core, and heat treated for maximum initial permeability.

The electrical conductor 44 is wound about the core 42 to form the coils of the antenna 38 (i.e., the toriod). The conductor 44 is preferably sheathed in CAPTON, or any other suitable dielectric material. The sensor antenna 38 preferably is vacuum-potted in an insulating epoxy 46. In the preferred embodiment, the epoxy comprises TRA-CON TRA-BOND F202 or equivalent. Electrical leads of conductor 44 pass through a passage 48 to a sealed hatch 50 in the drill collar, as is known in the art. Hatch 50, for example, houses the electronics for providing transmitting signals to and/or receiving signals from antenna 38. The electronics is in communication with downhole sensors, a power source, downhole memory and signal processor, as is well known. An electric field gen-

erated by the toroid couples a current into the drill string.

Further, electric transmitter/receiver assembly 26 may be of the type described in U.S. Patent No. 5,160,925 which is expressly incorporated herein by reference (e.g., antenna 25 and associated hardware). Alternatively, an electric field applied across an insulating joint as a source, may be used to generate a current in the drill string (i.e., direct-coupled) as is known in the art.

Electric/acoustic repeater assembly 28 comprises an electric transmitter/receiver in communication with an acoustic transmitter/receiver. The electric transmitter/receiver is preferably the same type as electric transmitter/receiver 26 described hereinbefore. The acoustic transmitter/receiver is preferably the same type as described in U.S. Patent No. 5,128,901 which is expressly incorporated herein by reference. Electrical communication is provided between the electric transmitter/receiver and the acoustic transmitter/receiver. These interfacing signals may require processing in accordance with the prior art teachings incorporated above.

Acoustic transmitter/receiver 29 is also preferably of the same type as described in U.S. Patent No. 5,128,901. Further, it will be appreciated the method of acoustic transmission may be in accordance with any of the methods taught in U.S. Patent Nos. 5,128,901, 5,128,902 and 5,148,408.

One advantage of the present invention is that the electric transmission is only needed at large depth from the surface. The resistivities are usually not as low at large depths because the porosity is reduced due to the high pressure. By using the model described in Wait et al the attenuation against source receiver distance is plotted in FIGURE 7 for a 1.0 ohm-meter formation for frequencies of 1, 5, 10, 15 and 20 Hertz. At 1.0 ohm-meter, a 10 Hz signal is attenuated at the rate of only 16.8 dB per 1000 feet (300m). This attenuation rate should allow for at least 5000 feet (1500m) of transmission. If greater distances are required the frequency can be lowered or an electric to electric repeater can be added, as is known. Unfortunately, the addition of an electric-electric repeater would reduce the data rate by a factor of two, because the repeater can not transmit and receive at the same time. In any case, the electric-acoustic repeater 28 is the upper most repeater in the drill string and is expected to have a range of at least 7000 feet (2100m). With the acoustic signal covering the top 7000 feet (2100m) and the electric signal covering the bottom 5000 feet (1500m) the telemetry system of the present invention can operate to 12000 feet (3600m) even under difficult conditions. Again using the Wait et al model the attenuation against source receiver distance is plotted in FIGURE 8, for a 10.0 ohm-meter formation for frequencies of 1, 5, 10, 15 and 20 Hertz. The attenuation rate is 6.7 dB per 1000 feet (300m) at 10 Hz so the electric signal can travel about 13000 feet (3900m) giving a total depth of 20000 feet (6000m) in this more resistive formation (i.e., 7000 feet (2100m) acoustic transmission and 13000 feet (3900m) electric transmission). The same depth can be achieved in more conductive formations by either adding electric-electric repeaters or reducing the frequency, both of which would reduce the data rate.

In the case of horizontal drilling, the angle between the electric transmitter and the electric receiver could be as high as 90 degrees. A drill string having a changing dip can be modeled using an electric dipole source. The electric dipole is a very poor approximation near the source, but it is correct for large distances as the current on the surface of the drill string will die off faster than the field of the electric dipole. This limit will be reached faster in conductive formations or for the higher frequencies. Referring to FIGURE 9, an electric dipole model for the attenuation against source receiver distance is plotted for a 1.0 ohm-meter formation for frequencies of 1, 5, 10, 15 and 20 Hertz. Near the source (i.e., small distances) the electric dipole plot markedly differs from the equivalent Wait et al model shown in FIGURE 7. However, at 5000 feet (1500m) the attenuation rates for both models are nearly the same for the higher frequencies. This indicates that the model with the drill string (i.e., FIGURE 7) has nearly reached the limit where it acts much like a dipole source. Therefore, we have used the dipole source model (FIGURE 9) to develop the attenuation against source-receiver angle plot (FIGURE 10) for a source-receiver separation of 2000 feet (600m) and a resistivity of 1.0 ohm-meter. This clearly indicates that a null angle in the data does not occur. Further, for situations where the dipole approximation is not valid there can be no null angle because the electric current to the drill string is still a dominant component and this current will follow the drill string around any corner.

In summary, uphole telemetry in accordance with the present invention comprises an electric current induced in drill string 16 by electric transmitter 26. The electric current contains encoded information of downhole conditions as is well known. This electric current travelling up drill string 16 is detected at the electric receiver of assembly 28. The received signal is processed to drive the acoustic transmitter of assembly 28. An acoustic signal containing the encoded information is induced into drill string 16 by the acoustic transmitter of assembly 28 and permeates up the drill string to acoustic receiver 29. This received signal is processed and utilized to evaluate and/or optimize the drilling process, as is known. As described hereinbefore, an electric-electric repeater may be employed for greater depths. Also, an acoustic-acoustic repeater may be employed for greater depths.

Downhole telemetry in accordance with the present invention comprises an acoustic signal induced in drill string 16 by acoustic transmitter 29. The acoustic signal contains encoded information of uphole commands as is well known. The acoustic signal travelling down drill string 16 is detected at the acoustic receiver of assembly 28. The received signal is processed to drive the electric transmitter of assembly 28. An electric signal containing the encoded information is induced in the drill string by the electric transmitter of assembly 28 and travels down the drill string to electric receiver 26. This received signal is processed and utilized to command a downhole processor (i.e., computer) as is known.

It is an important feature of the present invention that the acoustic telemetry is located away from the noisy downhole environment. The downhole noise presents a significant problem in efficient acoustic telemetry. It is further an important feature of the present invention that the electric telemetry is not located uphole where detection at the surface has posed a significant problem. The present invention resolves these problems by utilizing: (1) electric telemetry downhole, thereby avoiding the problem of detection at the surface; and (2) acoustic telemetry uphole, thereby avoiding the problem of acoustic noise near the bit (i.e., downhole).

While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation.

Claims

1. An apparatus for transmitting information through a drill string (16) having an upper end and a lower end with a drill bit (23;34) disposed at the lower end, comprising:
   means (26) for transmitting an electromagnetic data signal from a first location near the lower end of the drill string;
   means (28) for receiving said electromagnetic data signal at a second location between the lower and upper ends of the drill string;
   means (28) for transmitting an acoustic data signal from said second location in response to said electromagnetic data signal received; and
   means (29) for receiving said acoustic data signal at third location at or near the upper end of the drill string.

2. An apparatus for transmitting commands through a drill string having an upper end and a lower end with a drill bit (24;34) disposed at the lower end, comprising:
   means (29) for transmitting an acoustic command signal from a third location at or near the upper end of the drill string;
   means (28) for receiving said acoustic command signal at a second location between the upper and lower ends of the drill string;
   means (28) for transmitting an electromagnetic command signal from said second location in response to said acoustic command signal received; and
   means (26) for receiving said electromagnetic command signal at a first location near the lower end of the drill string.

3. The apparatus of claim 1 further comprising:
   means (29) for transmitting an acoustic command signal from said third location;
   means (28) for receiving said acoustic command signal at said second location;
   means (28) for transmitting an electromagnetic command signal from said second location in response to said acoustic command signal received; and
   means (26) for receiving said electromagnetic command signal at said first location.

4. The apparatus of claim 1, 2, or 3 wherein the drill string further includes a motor (30) in communication with the drill bit (34) and wherein said first location is between the motor and the drill bit.

5. The apparatus of claim 1, 2 or 3 wherein the drill string further includes a motor (30) in communication with the drill bit (34) and wherein said first location is above the motor.

6. The apparatus of any preceding claim further comprising:
   means for repeating said electromagnetic data signal at a fourth location between said first and second locations.

7. A method for transmitting information through a drill string having an upper end and a lower end with a drill bit (24;34) disposed at the lower end, comprising the steps of:
   transmitting an electromagnetic data signal from a first location (26) near the lower end of the drill string;
   receiving said electromagnetic data signal at a second location (28) between the lower and upper ends of the drill string;
   transmitting an acoustic data signal from said second location (28) in response to said electromagnetic data signal received; and
   receiving said acoustic data signal at a third location (29) near the upper end of the drill string.

8. A method for transmitting commands through a drill string having an upper end and a lower end with a drill bit disposed at the lower end, comprising the steps of:

transmitting an acoustic command signal from a third location (29) at or near the upper end of the drill string;

receiving said acoustic command signal at a second location (28) between the upper and lower ends of the drill string;

transmitting an electromagnetic command signal from said second location (28) in response to said acoustic command signal received; and

receiving said electromagnetic command signal at a first location (26) near the lower end of the drill string.

9. The method of claim 7 further comprising the steps of:

transmitting an acoustic command signal from said third location (29);

receiving said acoustic command signal at said second location (28);

transmitting an electromagnetic command signal from said second location (28) in response to said acoustic command signal received; and

receiving said electromagnetic command signal at said first location (26).

10. The method of claim 7, 8 or 9 wherein the drill string further includes a motor (30) in communication with the drill bit (34) and wherein said first location is between the motor and the drill bit.

11. The method of claim 7, 8 or 9 wherein the drill string further includes a motor (20) in communication with the drill bit (34) and wherein said first location is above the motor.

12. The method of claim 7, 8, 9, 10 or 11 further comprising the step of:

repeating said electromagnetic data signal at a fourth location between said first and second locations.

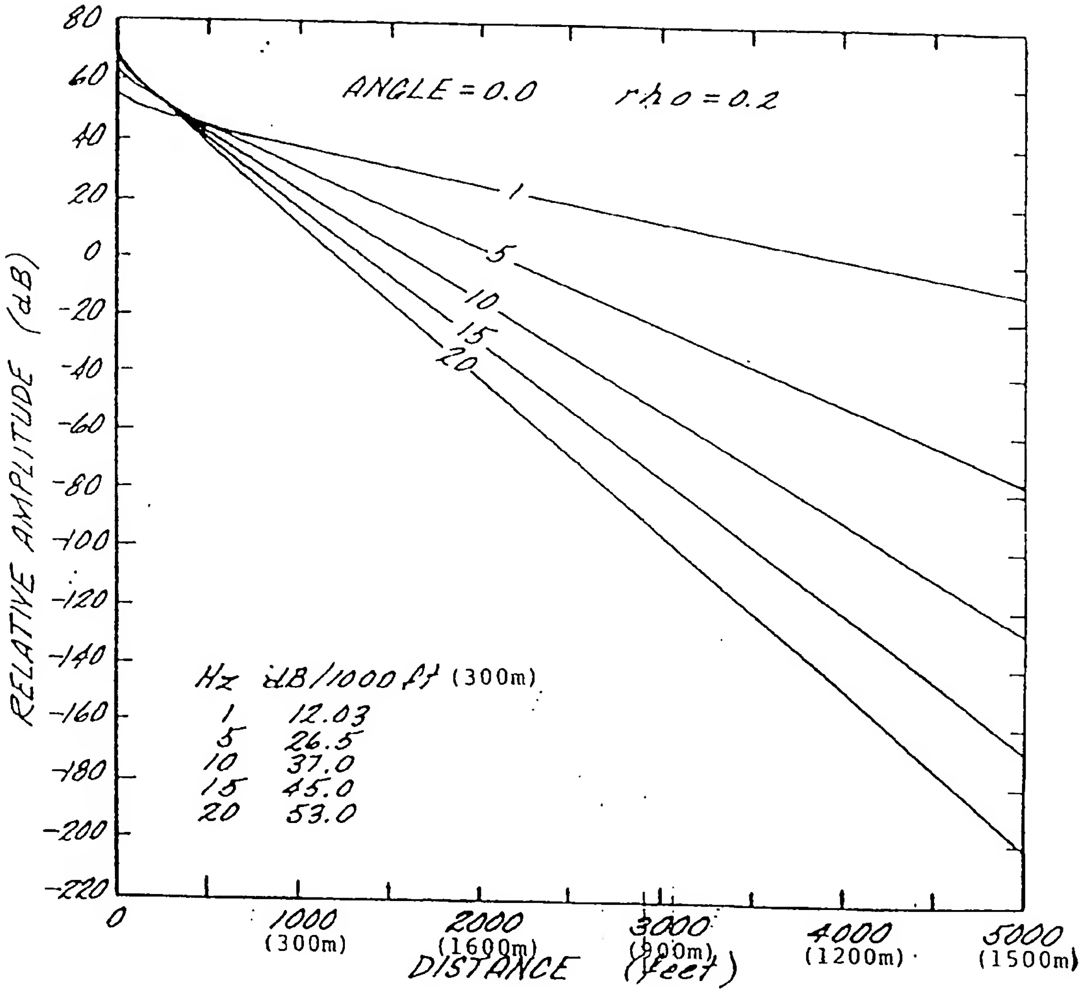
ANGLE = 0.0
rho = 0.2
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
RELATIVE AMPLITUDE (dB)
1
5
10
15
20
Hz dB/1000 ft (300m)
1 12.03
5 26.5
10 37.0
15 45.0
20 53.0
0
1000 (300m)
2000 (1600m)
3000 (900m)
4000 (1200m)
5000 (1500m)
DISTANCE (feet)

FIG. 1

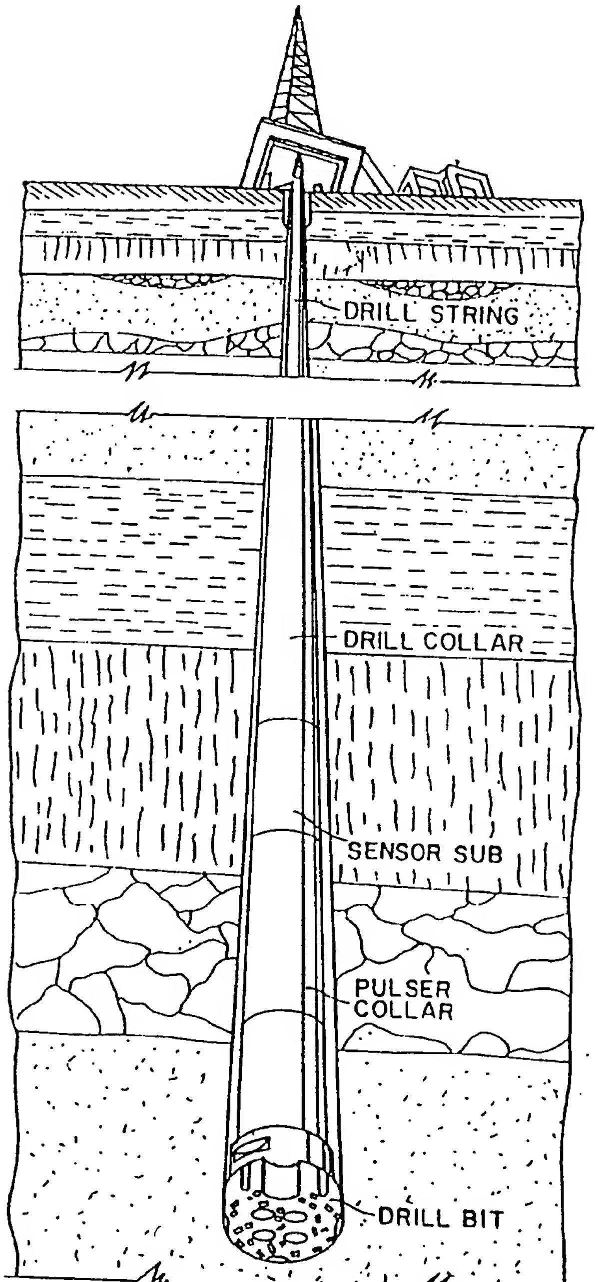

FIG. 2A
(PRIOR ART)

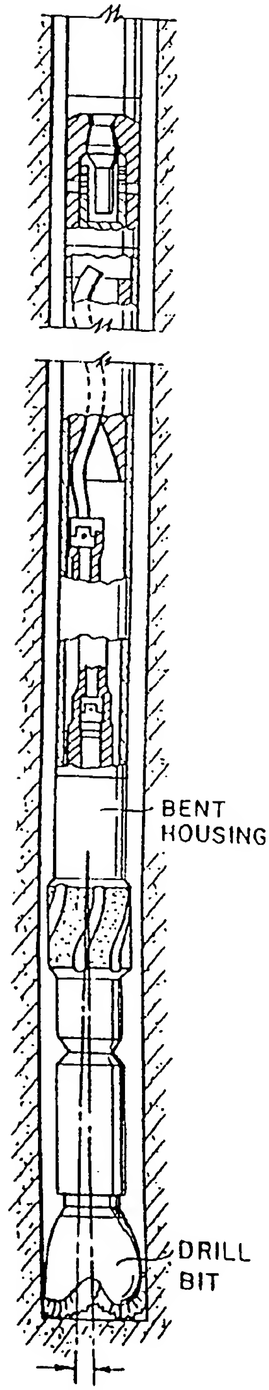

FIG. 2B
(PRIOR ART)

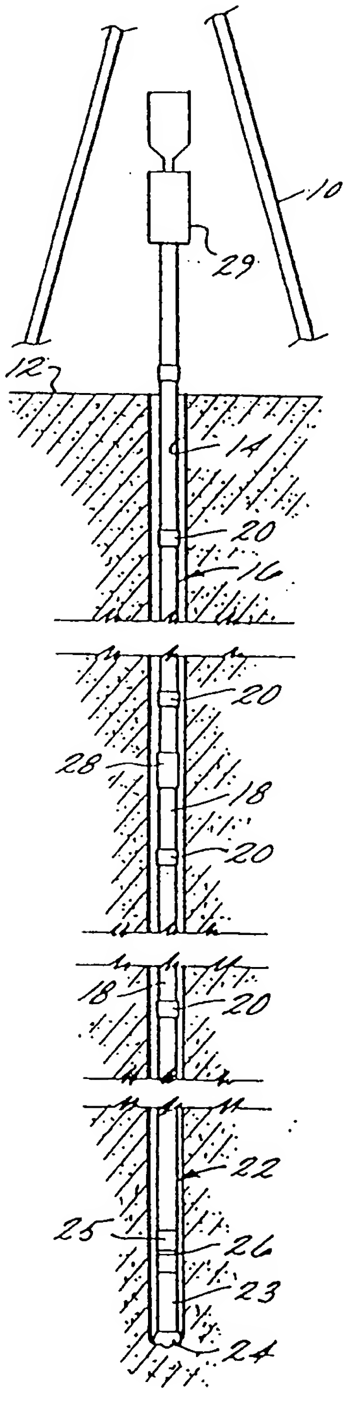
10
29
12
14
20
16
20
28
18
20
18
20
22
25
26
23
24

FIG. 3

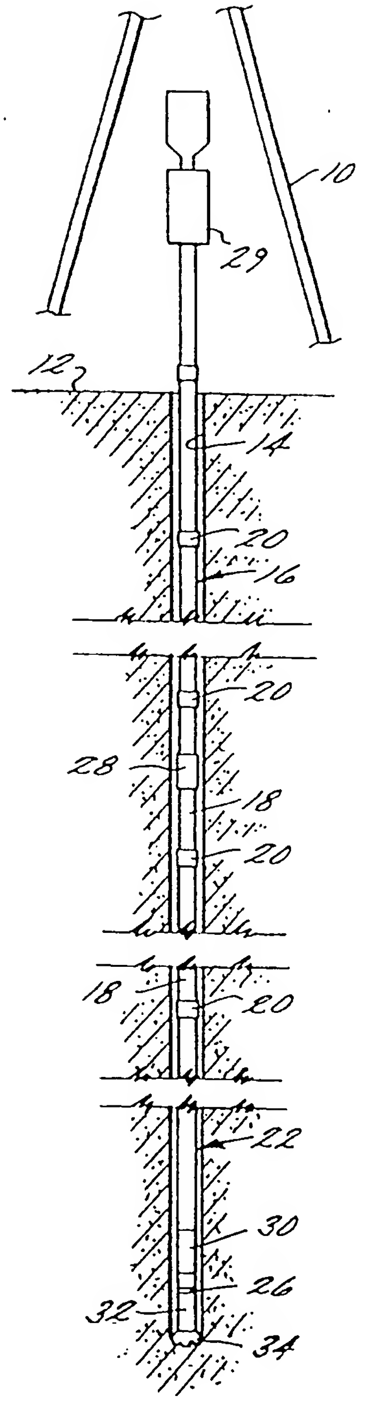
10
29
12
14
20
16
20
28
18
20
18
20
22
30
26
32
34

FIG. 4

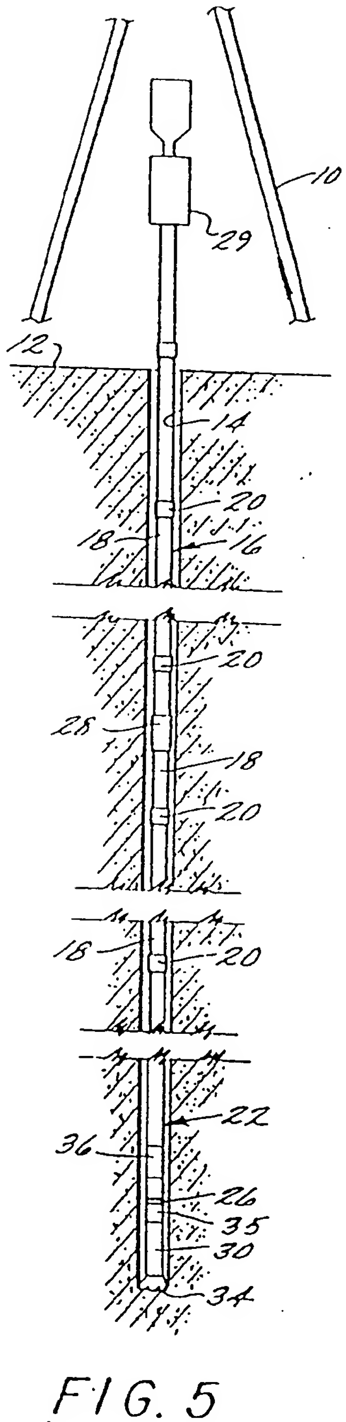
10
29
12
14
20
18
16
20
28
18
20
18
20
22
36
26
35
30
34

FIG. 5

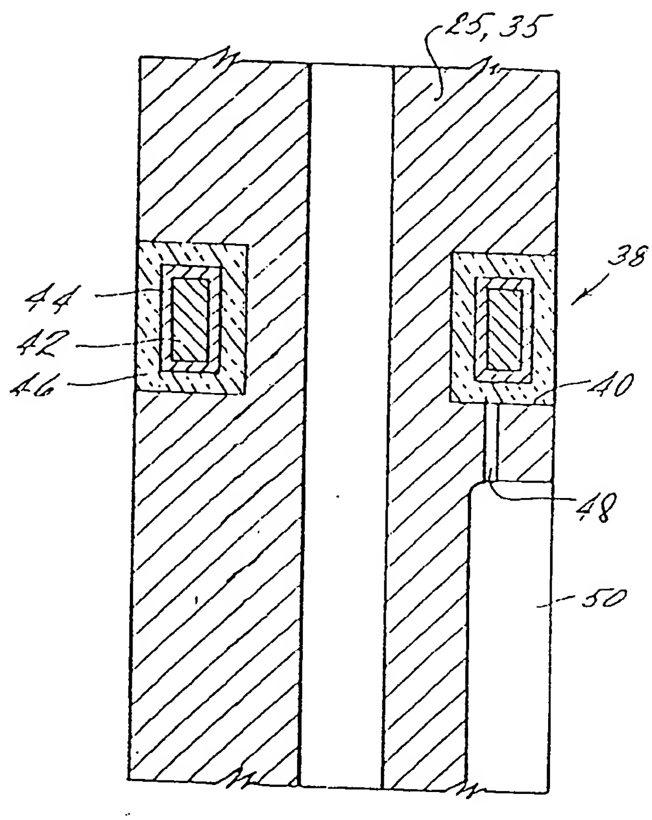
25, 35
38
44
42
46
40
48
50

FIG. 6

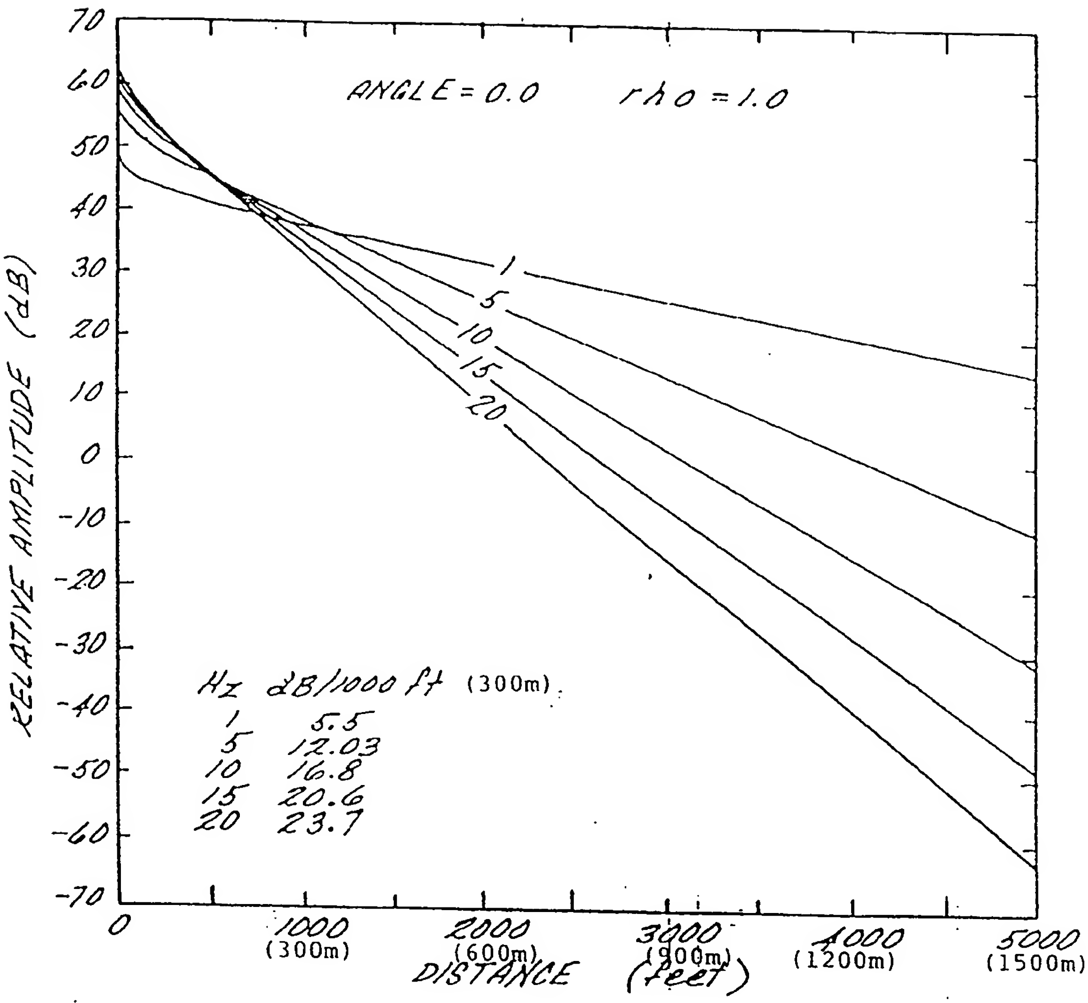
ANGLE = 0.0
rho = 1.0
RELATIVE AMPLITUDE (dB)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
1
5
10
15
20
Hz dB/1000 ft (300m)
1 5.5
5 12.03
10 16.8
15 20.6
20 23.7
0
1000 (300m)
2000 (600m)
3000 (900m)
4000 (1200m)
5000 (1500m)
DISTANCE (feet)

FIG. 7

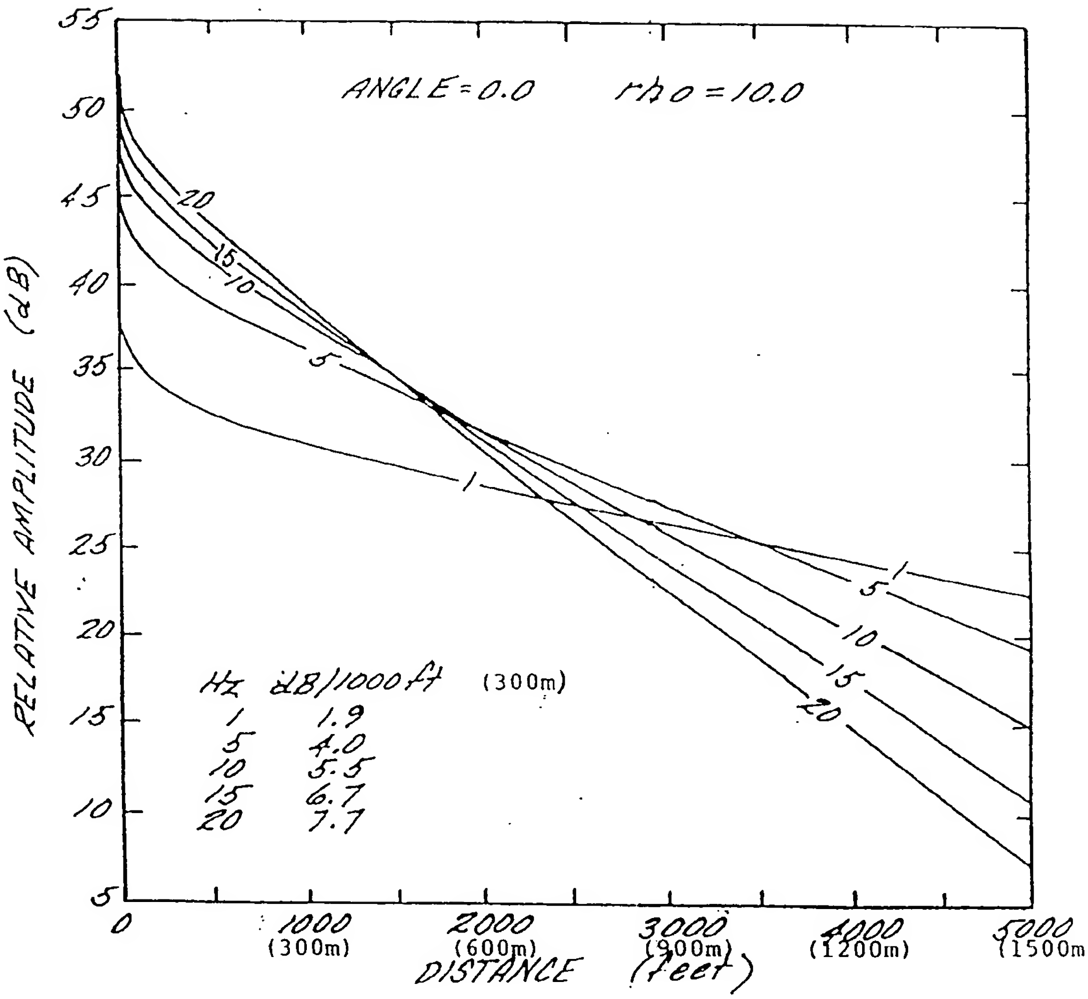
ANGLE=0.0 rho=10.0
RELATIVE AMPLITUDE (dB)
55
50
45
40
35
30
25
20
15
10
5
20
15
10
5
1
Hz dB/1000 ft (300m)
1 1.9
5 4.0
10 5.5
15 6.7
20 7.7
0
1000 (300m)
2000 (600m)
3000 (900m)
4000 (1200m)
5000 (1500m)
DISTANCE (feet)

FIG. 8

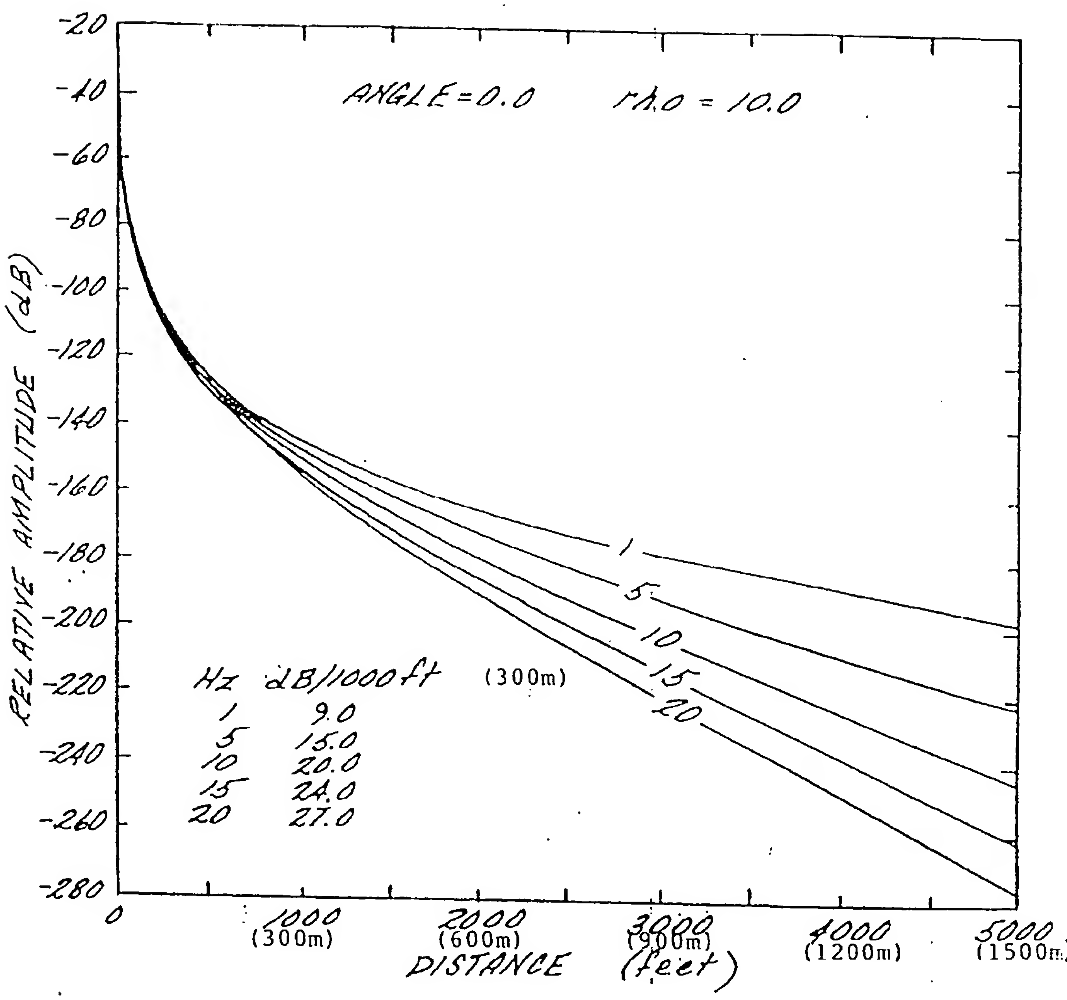
ANGLE=0.0 rho = 10.0
RELATIVE AMPLITUDE (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
-260
-280
0
1000 (300m)
2000 (600m)
3000 (900m)
4000 (1200m)
5000 (1500m)
DISTANCE (feet)
1
5
10
15
20
Hz dB/1000ft (300m)
1 9.0
5 15.0
10 20.0
15 24.0
20 27.0

FIG. 9

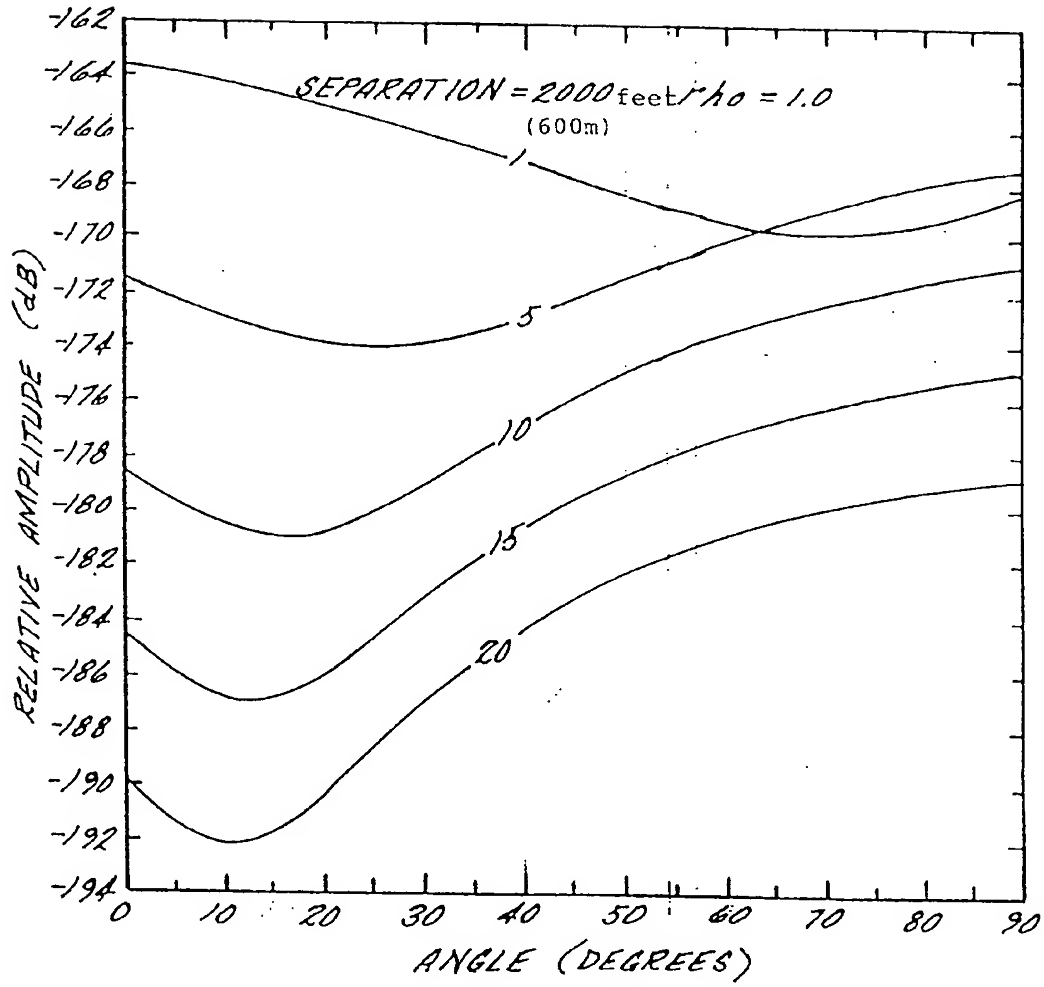
SEPARATION = 2000 feet (600m)
rho = 1.0
1
5
10
15
20
-162
-164
-166
-168
-170
-172
-174
-176
-178
-180
-182
-184
-186
-188
-190
-192
-194
RELATIVE AMPLITUDE (dB)
0
10
20
30
40
50
60
70
80
90
ANGLE (DEGREES)

FIG. 10

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

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(54) Method and apparatus for electric/acoustic telemetry in a well.

(57) A drill collar section (22) of a drill string (16) (i.e. at the downhole end of the drill string) includes an electric transmitter/receiver assembly (26) which communicates with an electric/acoustic repeater assembly (28) which communicates with an acoustic transmitter/ receiver assembly (29) uphole of the drill string by the transmission and receipt of electric and acoustic signals through the drill string. With drill strings that include downhole motors (30) the electric transmitter/receiver assembly may be positioned above or below the motor. Uphole telemetry comprises an electric current induced in the drill string by the downhole electric transmitter (26). The electric current contains encoded information of downhole conditions and travels up the drill string where it is detected at the electric receiver of the electric/acoustic repeater (28). The received signal is processed to drive the acoustic transmitter of the electric/acoustic repeater. An acoustic signal containing the encoded information is induced into the drill string by this acoustic transmitter and permeates up the drill string to the uphole acoustic receiver (29). This received signal is processed and utilized to evaluate and/or optimize the drilling process or to evaluate the earth formations being drilled. Downhole telemetry comprises an acoustic signal induced in drill string (16) by the uphole acoustic transmitter (29). The acoustic signal contains encoded information of uphole commands and travels down the drill string where it is detected at the acoustic receiver of the electric/acoustic repeater (28). The received signal is processed to drive the electric transmitter of the electric/acoustic repeater. An electric signal containing the encoded information is induced in the drill string by this electric transmitter and travels down the drill string to the downhole electric receiver (26). This received signal is processed and utilized to command a downhole processor (i.e., computer).

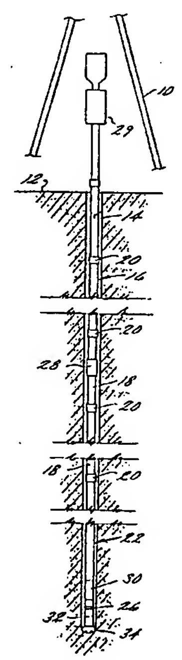

FIG. 4

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European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 94 30 5423

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X Y	WO-A-92 18882 (SMITH INTERNATIONAL) * abstract; figures 3-6 * * page 5, last paragraph * * page 27, last paragraph * ---	1,4,7,10 2,3,6,8,9,12	E21B47/12
Y	EP-A-0 195 100 (SCHILLING) * abstract * ---	2,3,8,9	
Y	US-A-3 793 632 (STILL) * abstract; figures 1,2 * ---	6,12	
A	FR-A-2 617 901 (ALSTHOM) * abstract; figures * ---	1,2,7,8	
A	WO-A-90 14497 (EASTMAN CHRISTENSEN) * abstract; figures * * page 6, line 7 - page 7, line 23 * ---	1,2,7,8	
P,X	EP-A-0 553 908 (ANADRILL) * abstract; figures 1,2 * * column 3, line 50 - column 4, line 38 * * column 9, line 47 - column 10, line 6 * * column 10, line 34 - line 53 * -----	1,4,7,10	TECHNICAL FIELDS SEARCHED (Int.Cl.6) E21B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	16 June 1995	Weiand, T

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
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E : earlier patent document, but published on, or after the filing date
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L : document cited for other reasons

& : member of the same patent family, corresponding document

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